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THE FINE STRUCTURE OF THE OCEAN: A REVIEW

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APPROVED FOR DISTRIBUTION

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TABLE OF CONTENTS

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ABSTRACT

Underwater acoustical measurements during World War II revealed small-scale inhomogeneities in the ocean attributed to small random scatterers. Not until 1963 did vertical sound-speed profiling reveal the layered nature of the phenomenon. Meanwhile, because oceanographic temperature and salinity profilers were not designed to detect these small-scale features, most oceanographic studies did not start until 1965 when higher-resolution equipment was widely available. Observations in many parts of the world have revealed the common occurrence of layered regions at many depths. The layers are quasi-homogeneous and range in thickness from a few centimetres to tens, or sometimes hundreds, of metres. Their horizontal extent is generally about one thousand times their thickness. Between the layers are thin boundary regions of sharp gradients in which fine structure, usually explained by billow turbulence between the layers, is sometimes observed. The formation of the layers is attributed to one or more of three broad processes: (a) horizontal transport, (b) vertical transport by thermohaline diffusion, and (c) vertical transport by dynamic instability. The details are still subjects of discussion and various explanations are reviewed. It is suggested that combined studies at sea, especially including joint oceanographic/acoustic measurements, might more quickly advance knowledge of the subject.

1. OBSERVATIONS

1.1 Acoustic Studies 1941-1967

The presence in the ocean of a finer structure than the classical two-layer system separated by a thermocline first attracted attention during World War II [Refs. 1 to 4] when the "scintillation" of direct sound waves was observed during sonar experiments. Although evidence of fine vertical thermal fluctuations was known to acousticians from sound-speed profiles [Ref. 5] and carefully made bathythermograms [Ref. 6], they preferred to study the fluctuations horizontally in the same general direction as the sound waves, even though this proved difficult [Ref. 5]. Small irregular fluctuations in the horizontal temperature gradient measured from sensors mounted on submarines were reported by Holter [Ref. 7] in 1946, by Urick et al [Ref. 8] in 1948 and by Liebermann [Ref. 9] in 1951; later measurements of this type, but incorporating water velocity probes, were made by Grant et al [Ref. 10] in 1963 and by Murphy et al [Ref. 11] with an unmanned vehicle [Ref. 12] in 1965. Theoretical studies by Berman [Ref. 13], Mintzer [Refs. 14-16] Stone et al [Ref. 17], Skudrzyk [Refs. 18-20] and Potter et al [Ref. 21], and measurements by Sheehy [Ref. 22], Whitmarsh et al [Ref. 23], Sagar [Refs. 24-26], Murphy et al [Ref. 27], Nanda et al [Ref. 28] and Whitmarsh [Ref. 29] between the late 1940s and early 1960s related the sound fluctuations to these inhomogeneities and envisaged an ocean comprised of small random scatterers. In Knollman's detailed study [Ref. 30] in 1964 of both US and USSR work he found mounting evidence that these scatterers were statistically spheroidal rather than spherical.

The belief in small random scatterers seems to have arisen because the horizontal temperature measurements showed "patch sizes" of less than a metre. As Stommel and Federov [Ref. 31] later demonstrated, this was probably caused because the sensors were passing horizontally through fine thermal layers that

undulated in response to internal wave motions. In addition, although Urick [Ref. 32] reported evidence of similar fluctuations at 1500 m depth in the Atlantic, much of this work was concerned with near-surface phenomena of interest to acousticians at that time; as Shvachko [Ref. 33] and Gostov and Shvachko [Ref. 34] have shown, inhomogeneities near the surface seem to be of an order of magnitude smaller than those in water that is an order of magnitude deeper.

It seems difficult to make too many comparisons between this early acoustical work of "thermal microstructure" and later studies under the same name made in and below the thermocline. The work of the acousticians was to understand sound fluctuations and not necessarily to explain ocean structures. It happened that, in a period when oceanographers were concerned with the large-scale, low-frequency movements of the ocean revealed by the lower resolution bathythermographs and Nansen bottles, the acousticians had higher resolution equipment that identified the effects of small-scale, high-frequency ocean features with which oceanographers were not yet generally concerned. That most underwater acousticians seemed to lose interest at the time that oceanographers gained interest seems indicated by Berman and Guthrie's 1950-70 review [Ref. 35] of underwater acoustics, whose section on "thermal microstructure" contains references dated no later than 1963.

In 1963, however, Piip [Ref. 36] of Lamont Geological Observatory, while studying the sound channel in the Bermuda-Barbados region with a vertical sound-speed profiler, had observed the "inhomogeneity of the oceanic waters, even at great depths and far from any sources — it seems as if large water masses, instead of mixing thoroughly during their long and slow journeys from the source, break up into layers and cells of moderate size. These "pieces" of water move about as discrete entities and stay this way for periods that must be measured in months, possibly years".

During the next four years Piip made similar observations in the same region [Refs. 37-41], in the Bahamas [Ref. 42], in the Bay of Biscay [Ref. 43], off Gibraltar [Ref. 43], near Madeira and in the Canaries [Refs. 43 and 44]. Very little of this work seems known to oceanographers.

1.2 Oceanographic Studies 1958-1972

The first report since the 1940s of a fine structure measured vertically by oceanographers seems to have come from Joseph [Refs. 45 and 46] of the German Hydrographic Institute working in the Irminger Sea in 1958 with thermocouples. Further measurements from the same area are reported by Holzkamm et al [Ref. 47], using the University of Kiel bathysonde [Refs. 48-51] which was also used in the early 1960s to record fine structure in the Baltic [Ref. 52], the Mediterranean outflow [Refs. 53-55] the Red Sea [Ref. 56] and its southern outflow [Refs. 57 and 58].

Although not the first to report fine layering, the description by the US/USSR team of Stommel and Federov [Ref. 31] of their 1965 observations in the tropical Pacific is generally considered to be the classical paper that marks the beginning of the oceanographers' work on the subject, probably because it is the first to suggest possible causes and to outline where future studies might go.

In 1965, also, observations were being made of an even finer structure between the layers. Fosberry of the Royal Navy and Woods of the U.K. Meteorological Office [Refs. 59-61] performed the first of a series of experiments in the summer thermocline near Malta using dye tracers, underwater photography and a temperature-gradient probe [Refs. 62 and 63]. These studies were continued and extensively reported by Woods [Ref. 64-68] during the next five years and did much to draw attention to the subject.

In this area he observed layers of near-constant-gradient water a few metres thick separated by interfacial regions composed of ensembles of steep-gradient "sheets" a few centimetres thick. He interpreted this finer structure as due to shear along the interfaces between the layers causing Kelvin-Helmoholtz instability and billow turbulence, which he saw [Refs. 69-71] as a process similar to that causing clear-air-turbulence (CAT) [Refs. 72 and 73] in the atmosphere.

The commercial production of a high-resolution salinity-temperature-depth profiler [Refs. 51 and 74] in the US in the early 1960s had made it easier for more oceanographers to observe fine structures. Since then, vertical measurements of fine structure have been made with these and similar instruments, as well as with specially-designed probes [Refs. 62-63 and 75-78] of generally higher resolution, in many parts of the world. A geographical listing of recorded observations is given in Table 1 and some examples of the data in Table 2.

As a result of the observations listed in Table 1, the picture of the ocean that has emerged is described by Nasmyth [Ref. 86] as one of fairly extensive regions of uniform gradients interspersed with horizontally-stratified regions that occupy between one-third to one-half of the total volume. These latter regions may vary from a few metres to a few tens of metres in thickness, extend horizontally for tens of kilometres and exhibit an irregular temperature structure quite unrelated to the mean gradients in the area. Within them are a number of irregular layers, typically a few centimetres to a few metres thick, separated by thin boundary regions (Woods' "sheet ensembles") of relatively steeper temperature gradients often exceeding 0.01°C/m.

Many questions remain unanswered about the formation and extent of the finer "sheet" structures. They have not been observed between all series of layers, but whether this is due to the small amount of shear or to the low resolution of the instruments is not yet clear and more studies are required in this direction, especially with the high-precision equipment being developed at Scripps Institution of Oceanography by Cox et. al [Ref. 80]. When observed, the finer structure in the "sheets" is generally accepted to be a result of the layering in the way envisaged by Woods [Ref. 68], so the principal question remains that of explaining the layers themselves.

TABLE 1

REFERENCES TO FINE LAYERING

PACIFIC	
East Indies	[31]
Hawaii	[76]
East tropical	[79]
San Diego Trough	[80-85]
Off Oregon	[86,87]
Gulf of Alaska	[88,89]
ATLANTIC	
Gulf of Mexico	[90]
West Indies	[36-41]
Florida-Bahamas	[36,42,68,79,91]
Bermuda	[36-41,92]
Tropical mid-Atlantic	[93,94]
Mid-Atlantic Ridge	[95]
Canaries	[43,44]
Mediterranean outflow	[43,44,53-55,96-102]
OWS Juliett	[103]
Irminger Sea	[45-47]
Irish Sea	[104]
BALTIC	[52]
MEDITERRANEAN	
Gulf of Lions	[105,106]
Tyrrhenian Basin	[107]
Strait of Sicily	[59-61,64-69]
RED SEA	[56,108,109]
INDIAN OCEAN	[57,58,110]
ARCTIC	[111-115]
ANTARCTIC	
Weddell Sea	[116]
Saline lakes	[117-119]
FRESH LAKES	
Lake Ontario	[79]
Loch Ness	[120]

TABLE 2

EXAMPLES OF FINE LAYERING

Place	Pacific	St.Sicily	Med.Outflow in Atlantic	Arctic	Tyrrhenian Basin
Ref.	[31]	[67]	[101]	[113]	[107]
Depth (m)	130-500	0-100	1200-1500	250-400	650-1900
Rel. to thermocline	in	in	below	-	below
* Layer thickness (m)	2-40	1-12	34	3	10-200
Interface thickness (m)	-	0.1-0.2	7	0.1	1-4
Δt across int. (°C)	0.04/m	1°/m	0.3	0.02	0.05-0.1
Δs across int. (‰)	n.a.	-	0.058	0.01	0.02
*Horizontal Extent (km)	2.20	n.a.	>30	n.a.	130

* A general rule is that layers have a vertical/horizontal ratio of 1:1000

2. EXPLANATIONS

The theories developed fall under three principal headings: (a) horizontal transport, (b) vertical transport by thermohaline diffusion, and (c) vertical transport by dynamic instability. It was once thought necessary to explain all layering by a single process but there is a growing tendency to choose the theory according to the circumstances. A recent example of this is an analysis in which Gregg and Cox [Ref. 85] see evidence of six distinct processes occurring along one profile.

2.1 Horizontal Transport

The early records of fine layering in the Irminger Sea [Refs. 45-47] were interpreted by Holzkamm, Krause and Siedler [Ref. 47] as being caused by the sinking of surface water combined with the horizontal mixing of waters of different characteristics. Piip [Refs. 36-44] attributed his observations in other parts of the Atlantic to the same cause. Similar processes were suggested by Stommel and Federov [Ref. 31] as a preliminary to double-diffusion, and later incorporators of the double-diffusion theories generally require advection [Refs. 53-58, 95, 102 and 121-124] as an initial process.

Pingree [Refs. 97 and 99] has suggested that advection along deep isopycnal surfaces could be originated by vigorous local mixing. Simpson [Ref. 104] has also called on advection in an area of low tidal energy to explain layering in the Irish Sea, and Gregg and Cox [Ref. 85] have found evidence of advection in the San Diego Trough. However, in the USSR "Polygon" survey in the tropical Atlantic [Refs. 93 and 94], with which Federov is associated, advection seems to be rejected as a formative process.

2.2 Vertical Transport by Thermohaline Diffusion

Because the transfer of heat by molecular diffusion is a hundred times faster than that of salt, the ocean's thermohaline structure can be mariginally unstable under certain conditions [Refs. 112 and 125]. Laboratory and theoretical studies of double diffusion [Refs. 126-145], mostly associated with the names of Stommel at M.I.T. and Stern and Turner at Cambridge, have indicated how these processes might be responsible for layering in the ocean. Federov [Refs. 122 and 146] has discussed ocean observations of layering in support of this concept.

The most frequent appeal to double diffusion is when warm salty water overlies cooler fresher water, so that both temperature and salinity decrease with depth. Tank experiments show that long thin convection cells grow from the interface, diffusing their heat more rapidly than their salinity and thereby continuing to descend. Similar conditions apply to the ascending elements. It has not yet been possible to observe these "salt fingers" in the ocean, although instruments for this purpose are being developed [Refs. 147 and 148]. Although some workers [Ref. 149] doubt if these delicate structures could survive in the ocean, Linden [Ref. 150] has recently demonstrated experimentally that salt fingering could still have a significant effect on vertical transport if turbulence in the open ocean is as patchy as reported by Grant et al [Ref. 151] and Woods [Ref. 68]. However, no theoretical work on the effects of shear on the fingers has yet been reported.

Stommel, who was among those who first drew attention to the physical curiosity of double diffusion [Ref. 152], used the process to explain the layering he observed in the Pacific [Ref. 31] and western Atlantic [Ref. 92]. The strongest circumstantial evidence, however, has come from observations of layering under warm salty outflows, such as that of the Red Sea into the Indian Ocean [Refs. 57, 58 and 110], the Mediterranean into the Atlantic [Refs. 43, 44, 53-55 and 96-102] and the Levantine waters of the eastern Mediterranean into the Tyrrhenian Basin [Ref. 107].

The stepped characteristics of layers in these areas is rather more uniform than observed in the thermocline layering and seems to be restricted to very specific parts of the area under the outflow [Refs. 100-102]. Huppert [Ref. 153] has made a theoretical analysis of double diffusion in which he calculates a life of five days for the layers observed by Tait and Howe [Ref. 96] in the Mediterranean outflow.

The other double-diffusion process occurs when warmer saltier water lies beneath cooler fresher water, so that both temperature and salinity increase with depth. Turner and Stommel [Ref. 125] have demonstrated that this can produce a series of well-mixed turbulent layers separated by sharp interfaces, again forming a regular stepped structure. Such a thermohaline profile is common in polar waters and apparently-permanent stepped structures of this nature have been observed there [Refs. 111-119]. Katz [Ref. 95] has shown that the penetration of saline Mediterranean water into a less-saline water column over the Mid-Atlantic Ridge results in the formation of sharp, well-defined layers. Similar thermohaline conditions can also exist above areas of heat transfer through the ocean floor and reports of layering have come from the "hot brine" areas of the Red Sea [Refs. 56, 108 and 109] and from parts of the Pacific [Ref. 154]; recent measurements in the latter area, however, have failed to confirm their continued existence there [Ref. 155]. Huppert's [Ref. 153] theoretical analysis of this process suggests that it can be one of great stability.

Gregg and Cox [Ref. 85] have recently suggested that the Soret diffusion effect, in which a temperature gradient tends to establish a salt concentration gradient, might be of significance in the formation of layers in regions of low vertical transport. More laboratory work is suggested to determine the Soret coefficients for the major constituents of sea water under oceanic conditions.

2.3 Vertical Transport by Dynamic Instability

Munk [Ref. 156] suggested that shear instability in inertia-gravity waves was a probable cause for vertical mixing in the thermocline and Phillips [Ref. 157] described how self-limiting breakdown of the waves would create turbulent patches that are sporadic in space and time but that, in the presence of a mean shear, would preferentially occur along the crests or troughs of the waves. Orlanski and Bryan [Refs. 158 and 159] proposed that a sporadic overturning associated with finite-amplitude internal waves of 10 m to 20 m vertical waveheight would convert a parcel of water of sloping density gradient into a homogeneous blob that would then find its own stability level and spread out in the form of a layer.

Garret and Munk [Ref. 160], however, envisage an almost closed system in which the shear between the layers is randomly superimposed on the shear of internal waves to cause local mixing, the creation of homogeneous parcels of water, and hence the formation of fresh layers. Although this concept of layering as a catalyst explains the regeneration of layers, it leaves open the question of how the first layers were formed and how, in a lossy process that must generate thinner and thinner layers, there is a return to the original thicknesses. However, their model is an important stage in drawing together some of the work on dynamic instability.

Woods [Ref. 161] has observed that 10 km long waves along the Maltese oceanic front cause upwelling and downwelling lobes of a few metres thickness, widths of a few kilometres, and lengths of over ten kilometres, which he associates with thermocline layers. It has not yet been possible to study this concept in other frontal areas and, moreover, it is not certain whether all layering occurs in the vicinity of fronts.

Atmospheric effects are thought to be responsible for some layering, even far from the surface layers. It is believed [Refs. 105 and 106], for instance, that cooling and evaporation of the surface in the Gulf of Lions by the Mistral sometimes causes the water column there to collapse and form deep intrusive layering.

Because of the non-linear properties of sea water, the mixture of two water masses of equal density but different thermohaline properties can be shown to result in a third mass of average thermohaline properties but slightly greater density. This "cabelling" instability was noted by Munk [Ref. 156] and has now been developed by Foster [Refs. 116, 162 and 163] as a possible explanation for the formation of steps in parts of the Antarctic. It may also explain conditions in the low salinity of "fresh" water lakes.

Many of the gaps in understanding the dynamic processes have been due to insufficient measurements of the velocities involved. The work being done by Nasmyth [Refs. 86 and 87], and such equipment as that developed by Simpson [Ref. 164], should help to provide these data.

CONCLUSIONS

The history of the study of fine layering in the ocean presents a sad picture of lack of communication between acousticians and oceanographers. The attempts of the acousticians in the 1950s to explain the inhomogeneities in terms of small random scatterers might have been resolved more quickly if the data had been published in oceanographic literature. Equally, the oceanographers' "discovery" in the late 1960s postdated wide-spread acoustic measurements that had already identified the layering in some detail but had not been widely published.

Explanations of the layered structure still depend on many theoretical suggestions based on a large number of observations but comparatively few detailed interpretive studies. Moreover, the observations have been made with many types of equipment having different time constants, and possibly not always under the most carefully controlled conditions [Ref. 165], so that it is difficult to compare one type of observation with another. It is suggested that a greater interchange between workers is required, not only in conferences but also in studying each other's areas with each other's equipment. The MODE experiment [Ref. 166] now being planned by 15 US and British laboratories under the leadership of Stommel and Robinson to study the ocean "weather" off Bermuda next spring will include a concentrated study of the layered structure and will, therefore, be a step in this direction. It is hoped that this cooperation will include further joint oceanographic-acoustic studies such as that recently undertaken by Johannessen and Mellberg [Ref. 167].

It is also suggested that the subject deserves a detailed cataloguing of the observations being made and an improvement in its nomenclature. The term "microstructure" has been deliberately omitted from this review because it seems

unsuitable as a description of everything between 200 m thick steps and millimetre thick "sheets". As the exact character of the structure becomes more precisely identified by the high-resolution equipment now coming into use it seems that a terminology based on statistical descriptions would aid communications.

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